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16. ABSTRACT This paper reviews relevant research findings for the purpose of establishing a set of uniform national criteria for designating locations of air monitoring stations. Data first are presented showing the difficulty, in the absence of uniform criteria, of interpreting measurements from one station in a city to determine if air quality for that city is "better" or "worse" than that for another city. Then, research data are given showing, for example, that proximity to traffic (in both the horizontal and vertical directions) affects measured carbon monoxide concentrations. The data suggest that monitoring station "coverage" could be improved by a dual monitoring approach that uses two continuous air monitoring stations at the same time.

Finally, a scheme is presented for classifying all monitoring stations into six different siting categories. Type A stations are designed to provide a realistic measure of pedestrian exposures, while Type B measures the background concentration extending over a large physical area. Type C stations monitor residential or suburban population exposures. Types D, E, and F are for more specialized purposes, such as collecting meteorological information and conducting air quality surveys. Types A, B, and C, which are most important in implementing air quality standards, must have a uniform probe height of 3 ± 1/2 meters. A standardized system of site selection, such as the one proposed here, should greatly improve the comparability and meaningfulness of data obtained from different air monitoring stations throughout the Nation.

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Development of Criteria for Siting Air Monitoring Stations

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A critical problem arises if one attempts to compare data from air monitoring stations in different cities, because there are so many differences in monitoring site locations. Some air monitoring stations are on the 6th and 8th floors of tall buildings in downtown areas; some are at ground level beside streets with heavy traffic; some are in residential areas with little traffic or industry; and some are in suburban or nonurban areas. Unfortunately, there is ample evidence that the location of a monitoring station relative to nearby sources (such as highways) affects the values observed at the station, particularly for carbon monoxide and other vehicular pollutants. Thus, a standardized system of site selection, such as the one proposed here, appears essential to improve the comparability and meaningfulness of data obtained from different air monitoring stations throughout the Nation.

Serious problems arise in attempting to compare data obtained from air monitoring stations located in different cities. A principal reason is the many differences in locations of the stations. Some air monitoring stations are on the 6*th* floor or higher of tall buildings in downtown areas; some are at ground level beside heavily traveled streets in central business districts; some are in purely residential areas with little traffic and no industry; some are in suburban or "nonurban" areas. Unfortunately, there is ample evidence that the location of a monitoring station can affect the magnitude of the concentrations measured at the station, particularly for carbon monoxide and other vehicular air pollutants. This is because the location of the station (both height and distance) relative to sources affects the values observed at the station.

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This paper reviews significant research findings for the purpose of establishing a set of uniform criteria for classifying and designating locations of air monitoring stations. Such siting criteria, of course, must be closely related to the fundamental purpose of an air monitoring network.

Statement of Problem

Table I shows the annual (arithmetic) average carbon monoxide (CO) concentration and the annual (arithmetic) standard deviation of 1 hour values at stations across the U. S. in 1972. The top portion of the table lists the percentiles (deciles along with highest and lowest values) from an original list of 83 stations, with values ranked in order of decreasing annual average concentration. Of the 83 sites, the highest average value, 17.5 parts per million (ppm), occurred at Site 2 in New York City, and the lowest, 0.9 ppm, occurred at Magna, Utah. In 1972, 50% of the 83 U. S. stations had annual average CO concentrations of 3.3 ppm or less (Camden is at the 50 percentile), and 40% had annual average CO concentrations of 2.5 ppm or less (Redwood City is at the 40 percentile).

The lower portion of Table I shows the concentrations for 4 of the 83 stations operating in New York City at different site locations. At Site 1, the annual average concentration was 2.7 ppm, which is well below the value obtained when all 83 stations are averaged together (3.7 ppm). The range of concentrations for New York City—the difference between the highest value (Site 2) and the lowest value (Site 1)—was 14.8 ppm. When the 4 monitoring stations in New York City are excluded from the list of 83 stations, the highest concentration observed at the remaining 79 stations was 8.6 ppm in Trenton, NJ (not shown in the table). The range of CO concentrations for the other 79 stations—the difference between 8.6 ppm in Trenton and 0.9 ppm in Magna—was 7.7 ppm. Thus, the range of concentrations for the 4 New York sites (14.8 ppm) was nearly twice the range for the other U. S. cities (7.7 ppm). These data show that *the range of values encountered at different locations in one city can be greater than the range of values for all other U. S. cities taken together.*

This result demonstrates the difficulty of using air monitoring data from one station in a city to determine if air quality

Table I. Carbon monoxide concentrations at U. S. stations in 1972 (based on 83 site locations).

Percentile	Annual arithmetic mean (ppm)	Arithmetic standard deviation (ppm)	City
Total U. S. Stations			
Highest	17.5	9.5	New York City, NY (Site 2)
90%	6.3	4.7	Jersey City, NJ
80%	4.9	2.9	La[illegible], CA
70%	4.3	3.1	Los Angeles, CA
60%	3.8	3.4	Somerville, NJ
50%	3.3	2.1	Camden, NJ
40%	2.5	1.4	Redwood City, CA
30%	2.3	1.8	Santa Barbara, CA
20%	1.7	1.7	Spokane, WA
10%	1.5	1.0	Longview, WA
Lowest	0.9	1.0	Magna, UT
New York City Stations			
Site 1	2.7	1.6	New York City, NY
Site 2	17.5	9.5	
Site 3	10.9	5.6	
Site 4	8.1	4.3	

for that city is "better" or "worse" than that of another city. This problem can be illustrated graphically if a histogram of the CO concentrations at all 83 sites is plotted with the values for the 4 sites in New York City specifically marked (Figure 1). If just the data for Site 2 had been available, we would have concluded that New York City, in 1972, had the highest CO concentration of all the cities. However, if only the value from New York's Site 1 had been known, New York City's measured CO concentration would appear to be less than the concentration at half of the U. S. monitoring stations. In fact, New York City then would lie at the 42 percentile in Table I.

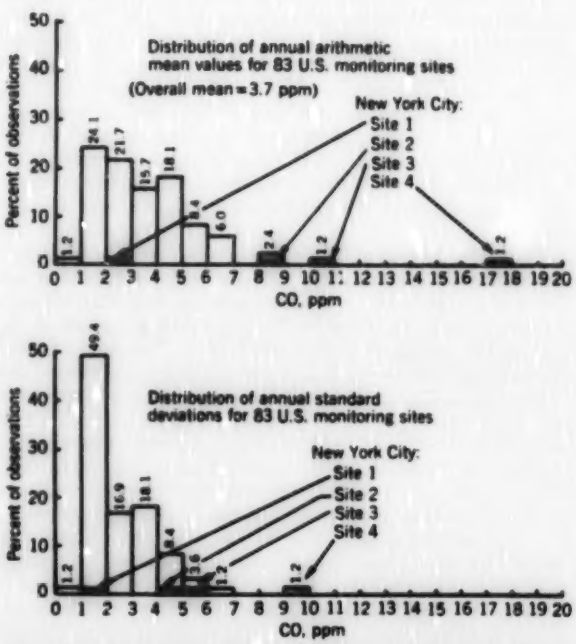

Figure 1. Annual arithmetic mean concentrations and arithmetic standard deviations (hourly averaging period) for carbon monoxide at 83 monitoring sites in U.S. cities in 1972. Source: EPA National Air Data Bank.

These problems can be attributed to the small number of monitoring stations per city and to nonstandardization with regard to their vertical and horizontal location. The problems illustrate the critical need for improved criteria for siting air monitoring stations on a national basis.

Formulation of Criteria

To formulate a realistic set of criteria for siting air monitoring stations, with emphasis on CO, I shall first review existing data showing the manner in which site location affects measured CO concentrations; then I shall propose a set of site location categories for air monitoring stations, each category having a different monitoring purpose.

An important concept in this analysis is *human population exposure*. Existing Federal National Ambient Air Quality Standards (NAAQS) specify particular concentrations that "are not to be exceeded more than once a year" in the "ambient air," which has been defined as "that portion of the atmosphere, external to buildings, to which the general public has access."[1] These standards therefore apply to all members of the general public outdoors, presumably at normal breathing level. I shall interpret the federal air quality standards in this context.

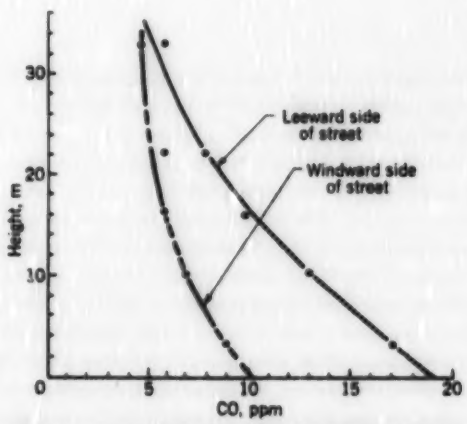

Figure 2. The vertical distribution of CO concentration on a street with traffic volume of 1500 vehicles/hour. Source: Ref. 3.

Survey of Research Findings

In general, air pollutant concentrations tend to decrease as source–to–receptor distances increase. Thus, when sampling is done very close to heavily traveled streets, CO concentrations are relatively high; as the intake probe is moved away from traffic—either horizontally or vertically—CO concentrations should decline.

Effect of Vertical Location (Sampling Height). Visits made to air monitoring stations throughout the country reveal wide differences in sampling heights. Some stations measure pollutant concentrations at 4 meters, others at 8 m, and some stations, located in tall buildings, measure concentrations at heights of 20 or 30 m. There also are variations in the heights of sampling probes relative to the stations themselves. In a nationwide survey of continuous air monitoring practices, Yamada[2] found probe heights varying 0.3 to 5 m above the roofs of monitoring stations.

There is considerable evidence, however, that the height of a sampling point affects the CO concentration observed, especially if measurements are made in the vicinity of major streets. In an extensive study of CO concentrations on three

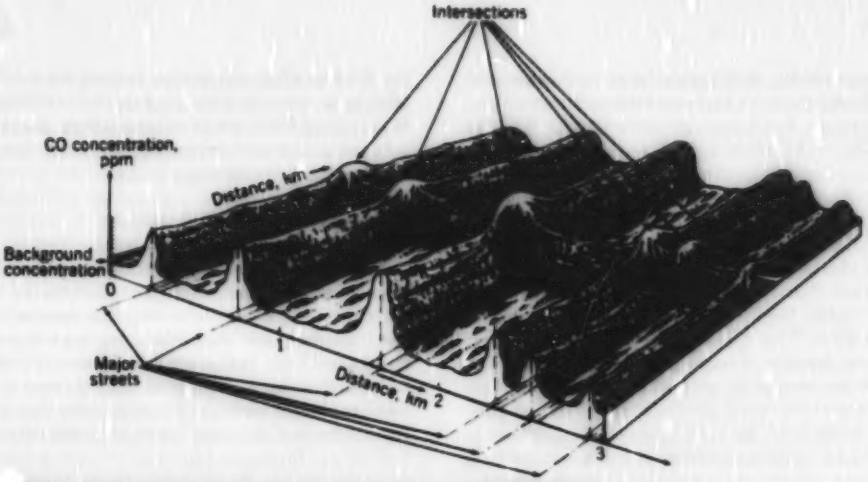

Figure 3. Inferred spatial distribution of vehicular air pollutant concentration (CO, Pb, etc.) in an urban area.

heavily traveled, downtown streets in Frankfurt/Main, Georgii[3] made measurements at five different heights. Figure 2 shows the resulting concentration profiles for both the windward and leeward sides of the street. The resulting data have been averaged for all three streets and for a variety of meteorological conditions. As can be seen, a significant gradient of CO concentration occurs with height. Average CO concentrations on the leeward side of the street decrease by more than 10 ppm as height increases from 3 m to 33 m. These results apply to streets with a traffic volume of 1500 vehicles/hr; for streets with less traffic, the gradient is less pronounced. Findings similar to Georgii's were reported by Schnelle[4] in Nashville, TN; by Johnson[5,6] in San Jose, CA; and by Ludwig[7] in St. Louis, MO.

Effect of Horizontal Location. Empirical data from specialized surveys[8-10] indicate that CO concentrations are very high close to heavily traveled streets (i.e., traffic volume greater than 400 vehicles/hr), declining rapidly as horizontal distance from these streets increases.

At horizontal distances greater than about 100 m, the CO contribution from a particular street declines to a negligible value, and an urban "background" concentration can be observed. At any given instant, this urban background CO is similar throughout large areas of 15 km^2, provided all measurements are made at sufficient distances from nearby streets. This consistency also holds for the long term average value of this background level (that is, 6-mo or 1-yr average). These findings were obtained from a large scale field data collection effort in which CO concentrations were measured at many different locations in an urban area and the results compared with values measured at an official air monitoring station.[8] From these findings, it is suggested that the inferred horizontal spatial distribution of CO concentration (long-term average) in urban areas is as shown in Figure 3. Here, the vertical axis depicts concentration, while the two horizontal axes represent distance (km) across the city. The undulating surface extending over the entire area depicts the background concentration, while the narrow ridges represent elevated concentrations near streets. This figure shows concentration ridges for 6 major streets (averaging more than 10,000 vehicles/day); many smaller neighborhood streets lie between the ridges but have traffic volumes small enough (less than 500 vehicles/day) that they do not contribute significantly to localized CO concentrations. The raised "mounds" where streets cross are the slightly higher CO concentrations observed at highway intersections.

Dual Monitoring Approach

Such research findings suggest the possibility of using a two station monitoring approach for CO—one station to monitor the lower urban background concentration and one to monitor the higher concentrations to which pedestrians are exposed near traffic. Such a pair of stations can be relatively close, but

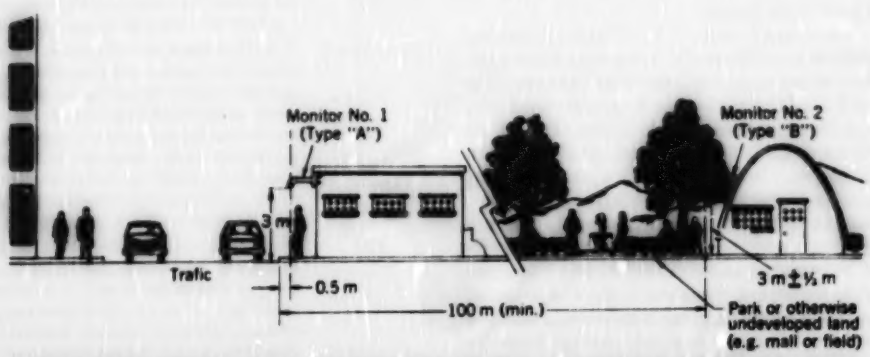

Figure 4. Simplified schematic of dual air monitoring system: Monitor No. 1 is the pedestrian exposure station; Monitor No. 2 is the background exposure station.

they remain at some minimum distance from each other and from sources. A *background exposure station*, for example, must be out of the range of influence of nearby traffic (greater than 100 m from the curb), while a *pedestrian exposure station* should have its sampling probe above a nearby sidewalk, perhaps ½ m away (horizontally) from the curb. This approach may be called a *dual monitoring system* (Figure 4).

Most of the outdoor urban population, at any instant of time, breathes air that is probably about 1 to 3 m above the surface of the ground. To measure the true population exposure, an optimum "mean breathing height" for the CO intake probe, therefore, is about 2 m. Practical problems arise at such low heights, however, because the probe can be easily reached by passersby, inviting tampering and, in some cases, vandalism. Although a protective shield probably could be devised, it is preferable to establish a national uniform height that is out of the way of people walking underneath. A height of 3± ½ m appears to be a reasonable choice for this national value.

Monitoring Site Categories

In the dual monitoring approach described above, the pedestrian exposure station provides a more realistic measure of the exposure of individuals on downtown streets. The background exposure station provides an improved measure of concentrations occurring over the greatest part of the physical area of the city. Unfortunately, few of today's air monitoring sites could be classified into either of these two categories.

Based on a review of research data on the spatial variation of CO concentration in urban areas, a simplified approach for classifying monitoring stations into six different siting categories (Table II) is proposed. Type A and Type B are criteria for the dual air monitoring approach described above. Type C, the residential population exposure site, supplements Type A and Type B by providing a measure of the background exposure of residential or suburban parts of the city. These residential background values should be meaningful for large urban areas, but in the smaller cities the values probably will not differ greatly from downtown background levels. The remaining site categories—Types D, E, and F—are intended for specialized monitoring purposes. Type D, the mesoscale meteorological station, would not be suited for determining compliance with Federal NAAQS, because the monitoring probe usually is much higher than the average breathing height of the general public. The Type E site category—nonurban background concentration—is especially suited for assessing the degradation of air quality in areas with very low concentrations. Type F monitoring sites, which are set up to assess the impact on air quality of some particular source, are suitable for determining compliance with federal air quality standards only when these stations are not on private property and probes are at breathing height.

If it were possible to classify most of the Nation's existing air monitoring stations into these six categories, their data could be interpreted more meaningfully. Furthermore, Site Types A, B, C, and E lend themselves quite readily to implementation of air quality standards, while Types D and F do not appear suitable for meeting the requirements of the Clean Air Act. Unfortunately, very few of the existing air monitoring stations have monitoring intake probes at heights of 3 ± ½ m. Most probes extend from monitoring station roofs and are probably more than 5 m above the ground. In some cases, very little effort would be required to lower the probe extensions to the 3 m level. A more serious problem is the site location itself. An examination of many existing sites reveals that too many fall between categories—for example, too far from the curb to give an estimate of the pedestrian exposure and too close to the street to avoid serious influence from the traffic. Such sites give ambiguous measurements. A standardized system of site selection, such as the one proposed here, could be adopted for the nation as a whole, greatly improving the comparability and meaningfulness of data obtained from different air monitoring stations.

Discussion

Although the air pollutants other than CO have not been discussed in detail, these site categories were established largely on the basis of the way the data would ultimately be used. Ludwig and Kealoha[11] have proposed siting criteria similar to these but covering additional uses. There appears to be little reason, if population exposure is to be monitored for compliance with the NAAQS, why the same site locations cannot be used for other gaseous pollutants as well. However,

Table II. Recommended criteria for siting monitoring stations.

Station Type	Description
TYPE A	*Downtown Pedestrian Exposure Station.* Locate station in the central business district (CBD) of the urban area on a congested, downtown street surrounded by buildings [i.e., a "canyon" type street] and having many pedestrians. Average daily travel (ADT) on the street must exceed 10,000 vehicles/day, with average speeds less than 15 miles/hour. Monitoring probe is to be located 1/2 meter from the curb at a height of 3 ± 1/2 meters.
TYPE B	*Downtown Background Exposure Station.* Locate station in the central business district (CBD) of the urban area but not close to any major streets. Specifically, no street with average daily travel (ADT) exceeding 500 vehicles/day can be less than 100 meters from the monitoring station. Typical locations are parks, malls, or landscaped areas having no traffic. Probe height is to be 3 ± 1/2 meters above the ground surface.
TYPE C	*Residential Population Exposure Station.* Locate station in the midst of a residential or suburban area but not in the central business district (CBD). Station must not be less than 100 meters from any street having a traffic volume in excess of 500 vehicles/day. Station probe height must be 3 ± 1/2 meters.
TYPE D	*Mesoscale Meteorological Station.* Locate station in the urban area at appropriate height to gather meteorological data and air quality data at upper elevations. The purpose of this station is not to monitor human exposure but to gather trend data and meteorological data at various heights. Typical locations are tall buildings and broadcasting towers. The height of the probe, along with the nature of the station location, must be carefully specified along with the data.
TYPE E	*Nonurban Background Station.* Locate station in a remote, nonurban area having no traffic and no industrial activity. The purpose of this station is to monitor for trend analyses, for nondegradation assessments, and for large-scale geographical surveys. The location or height must not be changed during the period over which the trend is examined. The height of the probe must be specified along with the data. A suitable height is 3 ± 1/2 meters.
TYPE F	*Specialized Source Survey Station.* Locate station very near a particular air pollution source under scrutiny. The purpose of the station is to determine the impact on air quality, at specified locations, of a particular emission source of interest. Station probe height should be 3 ± 1/2 meters unless special considerations of the survey require a nonuniform height.

the spatial distributions of other pollutants, such as oxidant differ from that of CO. Therefore, a similar analysis shoulc be conducted for each pollutant. For some pollutants, additional research is needed to establish their horizontal spatial variation at breathing level. This research should consist of carefully planned monitoring surveys similar in design to the CO research. In general, it is desirable, for economic reasons, to measure as many pollutants as possible at each air monitoring site. Therefore, any site selection criteria that evolve should not examine each pollutant separately but should treat them all as part of an integrated whole.

This paper has not dealt with the issue of how many sites of each kind are needed in a given urban area. That is a subject for *monitoring network design* studies. Very general criteria are available [12,13] for the minimum number of monitoring stations in any urban area, and some studies currently underway are addressing this topic from operations research[14] and diffusion modeling[15] points of view. My goal has been to focus on criteria for the site itself. The network design work should be extended to address the problem of how many sites of each category type are required in a given urban area and what factors influence this choice.

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